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Target development for the National Ignition Campaign

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ABSTRACT

Complex and precise research targets are required for the inertial confinement fusion (ICF) experiments conducted at the National Ignition Facility (NIF). During the National Ignition Campaign (NIC) the target development team embarked on and completed a science and technology campaign to provide the capability to produce the required targets at the rate needed by the NIC. Engineering design for precision, manufacturing, and fielding was developed. This required new processes, new tooling and equipment to metrologize and assemble components. In addition, development of new processing technology was also required.

Since the NIC had to respond to new results from ICF experiments, the Target Development team had to respond as well. This required target designs that allowed for flexibility in accommodating changes in the targets for capsules dimensions and doping levels, hohlraum dimensions and materials, and various new platforms to investigate new physics. A continuous improvement of processes was also required to meet stringent specifications and fielding requirements.

I. Introduction

Under the National Ignition Campaign (NIC) the Target Development team established the capability to develop, design for manufacturability, and fabricate capsules, hohlraums, and all the diagnostic and alignment components for ignition targets and targets required for supporting experiments. This effort also encompassed the equipment needed to manufacture, assemble, and characterize the target components, assemblies and procedures/techniques.

A. Ignition Target Design Development

The NIC required complex and precise targets to perform its mission. The most complicated of these are the indirect-drive cryogenic ignition targets. At the center of these targets is a ~2 mm diameter capsule that is filled with hydrogen fuel—in most cases, a solid layer of a 50:50 equimolar mixture of deuterium and tritium in equilibrium with its vapor at 1.3–1.5 K below the triple point at shot time. The capsule and the fuel are concentric and centered inside a high-Z hohlraum. An example of an ignition target with a 5.75 mm diameter hohlraum is shown in Figure 1.

Figure 1. A cryogenic ignition target.

A concentrated technology development program, with particular emphasis on precision engineering design with respect to applied materials research and development, has enabled the Target Development team to meet the stringent NIC requirements for capsule surface finish and positioning, performance at cryogenic temperatures, and robustness during assembly and fielding. Each target component was analyzed, and new designs and processes were developed, verified, tested, implemented, and documented. Assembly and tooling stations and procedures were created to meet target positioning requirements, and component design changes were implemented to improve assembly yield and throughput. Because requirements change due to experimental feedback, the target technology research and development must be continuous to keep pace. The Target Development team has excelled in providing precision targets for the NIC, showing a unique ability to respond dynamically as new targets are required.

The NIC ignition target consists of an ablator capsule and fill tube, hohlraum, LEH windows and inserts, tents, and the Thermal Mechanical Package (TMP). A TMP consists of silicon cooling arms, thermal shells, a diagnostic band, windows, heaters and sensors, tamping gas lines, and a wiring harness (see Figure 2).

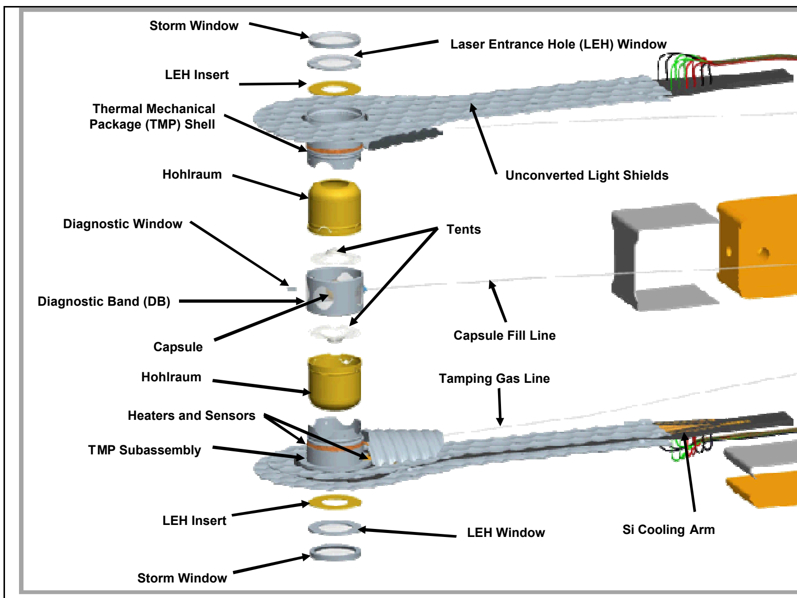

Figure 2. Exploded view of an ignition target.

Production of the capsule starts with a very smooth, very spherical plastic mandrel, the form on which the silicon-doped plastic is deposited uniformly as the mandrel is rolled or rotated. The mandrel material is chosen so that it depolymerizes into its monomer form at 300°C. The mandrel material is thus removed by heating, leaving the stable silicon-doped coating behind as the final shell. The silicon-doped shells are then characterized to ensure that they meet dimensional and dopant content requirements and are polished as appropriate to improve surface finish. A fill hole, typically ten microns in diameter, is then laser drilled into the capsule. A precisely drawn and finished glass fill tube is attached to the capsule for DT gas delivery [1, 2].

The ignition hohlraum is a gold or gold-coated (to prevent oxidation) uranium cylinder designed to couple as much laser energy to the capsule as possible. The layers are electro- or sputter-deposited on a precision-machined mandrel, which is etched away after deposition and machining are complete. The hohlraum is equipped with dual tori on the outer diameter for precision positioning within the TMP aluminum shell. A flange at the waist of the hohlraum supplies a stop for insertion in the shell and an attachment surface for the thin Formvar tent that holds the capsule in position. The LEH inserts are machined as separate parts to allow for various LEH diameters, and the LEH windows are aluminum coated, 500 nanometer thick polyimide film [3]. The diagnostic band joins and aligns the sub-assembled target halves and provides ports for characterization and diagnostic access.

The TMP (see Figure 3) precisely positions the hohlraum, manages the thermal environment of the hohlraum and capsule, and provides a modular platform for various diagnostic configurations without changes to the remaining components. The TMP consists of two aluminum shells joined by a band with cutouts to accommodate various diagnostics requirements. The design is modular and has been used throughout the ignition campaign.

The two silicon cooling arms attached to either end of the TMP assembly conduct heat away from the hohlraum to maintain the required temperature. These are lithographically etched to create a precise heat transfer path that ensures temperature uniformity in the target. Heaters located on the TMP shells are then used to produce a nearly spherical isotherm around the capsule. Tamping gas lines deliver helium gas to the hohlraum interior in order to reduce motion of the hohlraum wall and to facilitate propagation of the inner beams to the positions required for implosion symmetry.

Figure 3. TMP subassembly.

It is important to note that this generic overview of the target understates the complexity of target manufacturing. A target often consists of up to 500 individual precision-manufactured components, as specified by the particular target physics campaign. More detail on the ignition target design can be found in a paper by Alger et al. [4]

B. NIC Surrogate Physics Targets

A fundamental set of surrogate physics targets, fielded at cryogenic temperatures, are used as part of NIC (see Figure 4). These surrogate targets are not intended to produce ignition; instead, they generate essential physics information on target conditions to help refine ignition experiment parameters.

The Re-emit targets are used to tune early-time radiation symmetry in the hohlraum; the Keyhole targets are used to establish shock timing and power levels of the ignition laser pulse; the Convergent Ablator targets are used to measure the capsule trajectory (capsule radius versus time) and determine mass remaining at bang time (time of peak x-ray emission); and the Symcaps are used to adjust implosion symmetry. The Symcap is essentially an ignition target but with a thicker plastic capsule layer replacing the DT fuel. In an iterative process that has continued throughout the campaign, the implosion parameters are refined using these surrogate physics targets, and integrated experiments using an ignition target complete with a cryogenic fuel layer are then conducted to assess implosion performance.

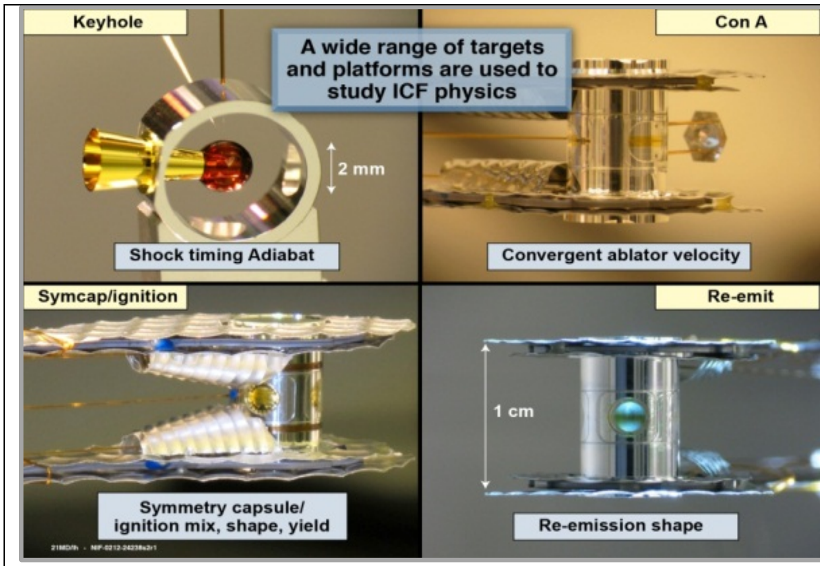

Figure 4. Surrogate physics targets used in NIC.

C. Major Target Modifications and New Target Designs

Often, modifications to existing target designs or new target designs are required to respond to the evolving needs of the ignition experimental program. For example, to measure the implosion trajectory over a longer time period, the viewing slit in the hohlraum for Convergent Ablator targets had to be increased significantly. The diagnostic axis and thus the location of the backlighter for this target were also changed to allow relocation of the primary diagnostic. This resulted in a significant reduction in diagnostic reconfiguration time, hence increasing the shot rate on NIF. The Keyhole target is another case where a major design modification was required. To resolve a physics issue relating to possible shock asymmetry in Keyhole shock timing experiments, the Keyhole target was redesigned to incorporate a small internal mirror to obtain shock transit information using the Velocity Interferometer System for Any

Reflection (VISAR) diagnostic from both the equatorial and polar directions of the capsule simultaneously. This modified target is called the dual-axis Keyhole target and is shown in Figure 5.

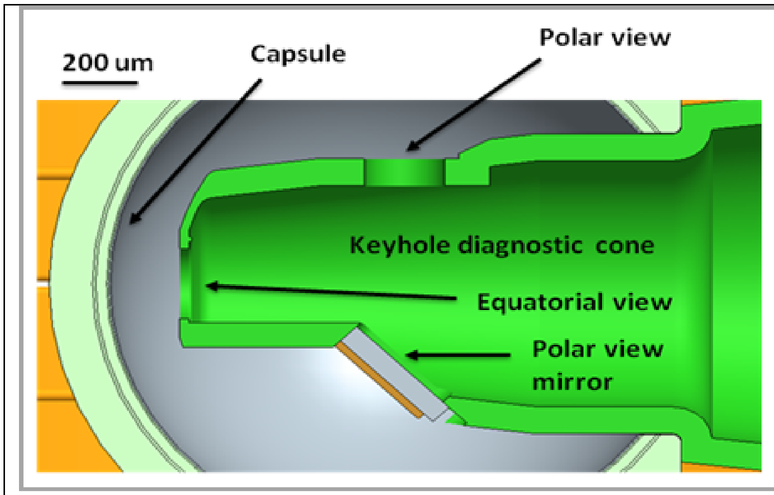

Figure 5. The Keyhole target was redesigned to incorporate a small mirror to support VISAR diagnostic data gathering.

During NIC, the ignition targets were modified to improve layering and reduce radiation losses through diagnostic openings by adding a heater to remove non-concentricity observed in solid fuel layers in depleted uranium hohlraums and gold coating the diamond window. The TMP was also redesigned to minimize the impact of future target scale changes and allow quicker response to changes in hohlraum size (length and diameter), shape (rugby), and case-to-capsule ratio (ratio of hohlraum to capsule dimensions). Ignition targets were also made impervious to frost formation by adding a second, warmer window, often called a "storm window," on the top of each LEH window.

In addition, the Target Development team responded to requests for completely new targets designs, all of which had to be designed and fabricated to meet the demanding experimental schedule. Examples of these included the Compton Radiography target, which uses a backlighter to image the cold fuel during the implosion; the Crystal Ball target, which diagnoses hohlraum drive pressure and timing by measuring the shock timing in materials where the equations of state are well known; and the View Factor target, which measures the radiation flux and temperature in a hohlraum at the capsule equator. See Figure 6.

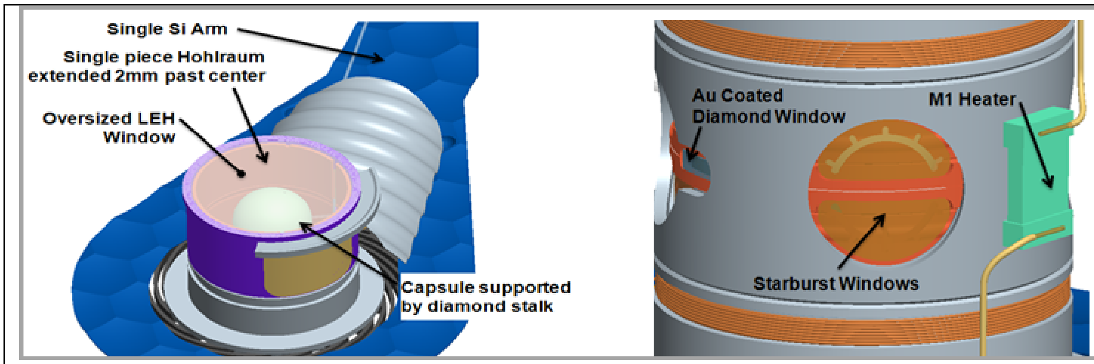

Figure 6. View Factor and tritium–hydrogen–deuterium target upgrades.

D. Continuous Improvements in Target Quality and Target Assembly

The extreme temperatures and pressures the targets encounter during experiments make the results susceptible to imperfections in fabrication. The specific manufacturing requirements for all NIF targets are extremely precise. Many components have to be machined to an accuracy of within one micron, or one millionth of a meter. Some gaps in joints can be no larger than 100 nanometers. Precise microassembly of the targets have error margins of less than three microns.

New tools to image and characterize materials have provided insight into target development progress and necessary changes in material preparation and fabrication. Continual improvements are also based on simulations and experiments at the Janus laser at LLNL, the OMEGA laser at the University of Rochester, and other facilities worldwide.

1. Capsule Finishing

Surface conditions for the assembled fuel capsules have stringent specifications, and most capsules require polishing to meet these specifications. In the case of plastic ablators, the major polishing concern is controlling isolated defects on the surface. The defects arise from submicron features in all dimensions on the mandrel; their size is such that optical detection is very limited. They evolve into 30–40 micron diameter bumps 200–800 nanometers in height on the finished capsule surface. Conventional polishing can remove the bumps but leaves scratches behind. A proprietary polishing technique has been developed that can remove or reduce bumps from 600 nanometers to less than 150 nanometers in height with minimal scratching. Larger bumps require a laser ablation step before polishing to reduce their height to less than 600 nanometers. Scanning electron micrographs show that polishing a plastic capsule improves its smoothness and consistency (see Figure 7). These capsule finishing techniques were developed in approximately one year.

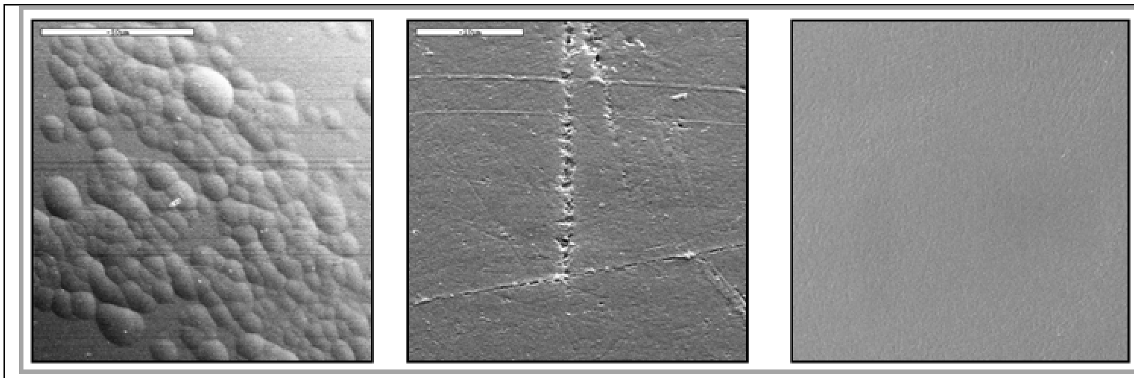

Figure 7. Scanning electron micrographs of capsule surface. Left to right: as-deposited, conventional polish, advanced finishing.

2. New Materials and Processes Developed

As the NIC experimental campaign has progressed, target physicists and target development engineers have collaborated to develop new materials and processes to enhance target performance and diagnosis and/or make target production more efficient. Examples of hohlraum design and manufacturing developments include:

- The use of micron-layered material coatings (of depleted uranium, for example).

- Precision doping of capsule ablators (by adding silicon to the capsule wall, for example) to enable the detection of specific x-ray signatures during a shot or to mitigate the effects of x-ray preheat.
- The addition of trace amounts of entrapped gases to the capsule (such as xenon) [5] for after-shot radioisotope forensics [6].
- New ablator materials (such as high-density carbon) for improved x-ray energy coupling [7].
- Modifications to the tent that positions the capsule inside the hohlraum (to reduce the amount of tent material and minimize capsule interaction during ablation) [8].
- Reduction of the fill tube diameter (from an already miniscule 10 micron diameter to less than 5 microns) to minimize its effect on capsule implosion symmetry.

Of particular note is the effort to reduce the fill tube diameter. The fill tube delivers fuel to the target and is thought to have a role in the initiation of the crystal growth of the ice layer. At issue was the possibility of an implosion asymmetry introduced by the fill tube, as it penetrates the capsule wall at one point. Moving to a smaller diameter fill tube could minimize the asymmetry effect but would require drilling a 5 micron hole through the 200-micron-thick ablator, a difficult 40:1 aspect ratio. Nevertheless, the engineering teams successfully completed the process engineering steps needed to make the fill tube area four times smaller—creating the new fill tube, drilling the desired hole, manipulating the smaller tube and gluing it in place, examining the effect of the smaller tube on capsule fill time [9], and finally putting all the processes through a rigorous scientific peer review. The result is a process that may increase the reliability of crystal seeding during fuel layering and reduce the capsule asymmetry. The problem is that the calculations are very difficult and the conclusions from the calculations, which do generate a non-negligible ablator mass injection into the fuel, could be optimistic) an achievement accomplished while continuously producing the current capsules required by the target physicists.

3. Target Assembly

Several methods have been used in target assembly to position the capsule in the center of the target, each with associated downsides relative to sealing joints at cryogenic temperatures. Currently, the most robust method for capsule positioning is threading the fill tube through a 200-micron hole in the diagnostic band, roughly positioning the capsule in the center of the band. The capsule fill tube assembly (CFTA) and diagnostic band are then moved into the final assembly station as a subassembly. This method has been repeatedly shown to be helium leak tight. The main concern when assembling the CFTA to the diagnostic band is protecting the capsule-to-fill tube joint, which is made with 5 nanograms (specification) of epoxy. The final assembly integrates two TMP subassemblies, the CFTA and the diagnostic band, simultaneously. It also integrates the target and the target cryogenic base.

An important consideration during final assembly is that the workstation and related characterization systems are aligned prior to and during assembly. Therefore, the final assembly machine is integrated on an Optical Coordinate Measuring Machine. Precision tooling used to bring the target halves together must keep the assemblies square to each other and properly clocked. Force and torque sensors are integrated into the final assembly machine to monitor any misalignment or binding. A critical element of the final assembly is capsule centering. The capsule is centered with respect to the hohlraum–LEH inner diameter via micrometer-driven stages, but once the tents engage the capsule, the position is controlled by the mechanical properties of the tent. Capsule centering metrology is done optically via microscopy and laser ranging.The NIC infrastructure for making and characterizing the precision cryogenic target components resides at GA. LLNL, on the other hand, is responsible for assembly of these components and the characterization of the "as-built" cryogenic targets (ignition and surrogate physics targets) used in the NIC experimental ignition program.

Target assembly is carried out at LLNL in a 3000-square-foot, Class 100 cleanroom (see Figure 8). The cleanroom is equipped with over 40 assembly stations with customized tooling, where target components are inspected, assembled, and tested to produce shot-ready, cryogenic targets for NIC.

Four distinct assembly lines have been developed to assemble the intricate NIC targets to the required precision. They are:

1. Tent subassembly line—used for fabricating, installing, and inspecting the Formvar membranes that support the capsule in the center of the target.
2. CFTA subassembly line—used for confocal microscopy 4π inspection and additional cleaning (if required) of the CFTA, and threading the CFTA into final assembly tooling.
3. TMP subassembly line—used to marry the hohlraum and LEH insert with the TMP.
4. Final assembly line—brings together the components and subassemblies from the other three lines and completes the integration of these components, including sealing the target so that it is leak tight at both room and cryogenic temperatures [10].

Figure 8. Cleanroom for fabrication and characterization of target components at General Atomics is shown on the left, while the cleanroom at LLNL for target assembly and characterization is shown on the right.

Fabrication of NIF ignition targets has evolved to a greater level of automation and determinism through the use of a new Precision Robotic Assembly Machine (see Figure 9) [11]. Error budgets supporting the fabrication and validation of critical assemblies have been formulated and validated through extensive metrology of completed targets. A suite of new assembly tools provides increased throughput with greater repeatability, while offering agility in accommodating varying size scales and novel target features. A process for rapid-close target assembly was designed and implemented to assemble a CFTA into an ignition target while maintaining capsule orientation.

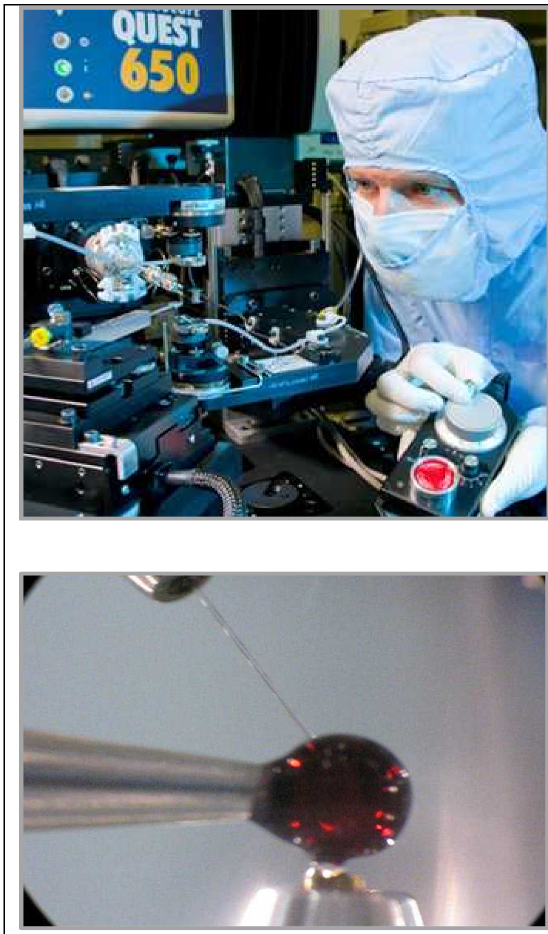

Figure 9. (Top) The Precision Robotic Assembly Machine used to manufacture fusion ignition targets. (Bottom) High-throughput capsule cleaning process uses a combination of chemical action (solvent choice) and physical entrainment (stream kinematics) to clean capsule surfaces with high efficiency.

Throughout the target assembly process, a critical element is cleanliness. Surface debris and imperfections can interfere with the uniformity of capsule heating and compression. The external and internal capsule surfaces are the smoothest surfaces fabricated during the target manufacturing process. The capsules undergo a multistep manufacturing process to ensure precision and performance reliability through interior and exterior capsule smoothness. Capsules are inspected and then subjected to a tumble polish. If during assembly any features or spots higher than 2 microns are detected, they are individually mapped (a 2 micron height variation on a 2000 micron diameter sphere represents a variation of 0.1% in height) and treated. A solvent stream jet is used to remove isolated particles adhering to the surface of the capsule. The cleaned capsule is inspected and characterized, and the capsule is then ready for final assembly into the target.

E. Target Fabrication and Manufacturing Infrastructure

To meet the demanding precision, schedule, and capacity requirements for manufacturing the wide array of targets used during the NIC, numerous capabilities have been put into place both at GA and LLNL. Further, processes have been developed and corresponding procedures have been documented to ensure high-quality component fabrication, target assembly, and characterization on a consistent basis. These have formed the basis of training for the target production workforce and for ensuring continuity and retention of expertise. The extraordinary capabilities and infrastructure developed and implemented for target fabrication and manufacturing under NIC will broadly support all NIF missions in the future.

1. Capabilities at GA (La Jolla, California)

The production of target components and subassemblies for NIC is carried out in numerous laboratories located on the main GA campus.

Precision Machining: A precision machining area includes seven precision lathes and three precision mills used in the fabrication of TMP components, LEH components, keyhole cones, mirrors, shells, and hohlraums. Two laser machining areas are used for drilling holes in plastic (CH), beryllium, and high-density carbon shells, and a laser ablation station that is used to remove isolated features on CH shells to reduce the effect of such defects on the implosion.

Mandrel Fabrication: Mandrels for CH capsules and beryllium shells are fabricated in a cleanroom.

Capsule Fabrication: Ten glow discharge plasma coating systems [12] are available for making capsules, five of which are dedicated to NIF CH shell fabrication. The other coating systems are used for depositing custom layers (such as copper or germanium) or silicon dopant layers used as x-ray preheat shields. Custom layering also includes the option to add small amounts of detector material at specific locations in the capsule to trace capsule material mixing into the central hot spot region. Capabilities have been introduced for polishing both CH and beryllium capsules. Glass exploding pusher target shells used for neutron diagnostic calibration at NIF are also fabricated and metrologized using the glow discharge polymer process.

Hohlraums: In addition to gold hohlraums, GA has facilities for fabricating depleted uranium (DU) hohlraums. A precision lathe is dedicated to machining DU and copper or aluminum mandrels used in DU hohlraum fabrication, and three coating systems are used to coat mandrels for DU hohlraum fabrication.

Subassemblies: Subassembly of the CFTA and TMP cans is performed in a cleanroom equipped with a number of customized assembly stations and specialized metrology equipment. A robotic assembly area has been qualified for production to automate the attachment of TMP cans to the silicon arms. This subassembly is a critical component of the final assembly at NIF, where the target is connected to the cryogenic base.

Beryllium: GA has a facility capable of safely handling beryllium, equipped with three beryllium sputter coating systems used in fabrication of beryllium shells [13].

Metrology: Several laboratories at GA are set up and equipped to carry out precision characterization [14] of NIC target components (TMP components, LEH components, keyhole cones, mirrors, mandrels, capsules, and hohlraums, and TMP and CFTA subassemblies). Capabilities include a Nikon Nexiv optical coordinate measuring machine equipped with custom analysis software for automated mandrel dimensional metrology.

GA fully characterizes NIC capsules using the following techniques (see Figure 10).

- **Phase Shifting Diffractive Interferometry (PSDI):** The PSDI functions by passing a single 532 nm laser beam through a beam splitter, which divides the beam into a reference and measurement beam. These beams are reflected to the interferometer and undergo constructive and destructive interference. Fringes are produced as the beams go in and out of phase, and a charge-coupled device (CCD) camera detects and displays the resultant interferogram. A delay in the beam is introduced by a piezoelectric transducer (PZT) that moves a total distance of approximately onehalf wavelength. A CCD image is taken each time the PZT moves 1/24 of a wavelength to generate twelve 2k by 2k pixel arrays. By fitting a sine wave to the 12 arrays, the phase angle is obtained for every pixel. This phase angle is directly proportional to the surface height at each pixel, resulting in a height map. Captured CCD images have a lateral resolution of ~1 μm and height accuracy of ~5 nm peak to valley. In its current embodiment, the interferometer uses 110 images (medallions) to capture all isolated and gently curved defects on the entire shell surface [15].

- **Atomic Force Microscopy (AFM):** Using the Spheremapper AFM tool to measure equatorial traces on a rotating shell, GA measures (high mode) surface roughness and (low mode) shell distortion to NIC specifications with 1 nm system noise. Until a few years ago, the Spheremapper sampled only a small fraction of the surface of the capsule, but with recent upgrades, the Spheremapper is now capable of providing complete (19 traces) and accurate measurements of the mid modes.
- **Contact Radiography:** GA developed a nondestructive technique to precisely profile graded dopants in ICF shells. This quantitative method can detect dopant variation to better than 0.1 atomic %. Contact radiography also provides accurate dimensional information through the proper corrections of various distortions induced by the imaging lens, the point projection geometry, and x-ray refraction.
- **Scanning Electron Microscopy (SEM):** Scanning electron microscopy with energy dispersive x-ray spectroscopy (EDS) is frequently used for quality assurance and monitoring contamination. GA uses this technique for determining NIC capsule dopant profiles and DU hohlraum microstructure.
- **X-ray microscopy:** A commercial (Xradia) point projection x-ray microscope is used to measure/characterize the laser drilled fill hole geometry to ~1.5 micron resolution.

- **Energy dispersive x-ray spectrometer (EDS):** GA developed a physics-based EDS model and fabricated standards to make it quantitative for low concentration of relatively light elements in a very low-Z matrix to examine NIC capsule contaminants and dopants.
- **X-ray Fluorescence (XRF):** Commercial XRF systems can only calculate elements atomic percent in flat samples. GA developed a unique XRF program for quantitative XRF computation on spherical samples. This method is accurate to 10% for high-Z elements and has the trace detection capability at a 1 ppm level for contamination control.
- **Precision Radiography:** GA designed and constructed a precision radiography system to measure x-ray opacity variation in an ablator capsule to 10^{-4} accuracy at 120-micron spatial resolution. Recent improvement in x-ray tube design enables complete full-surface measurements in one day. This instrument is unique in its ability to see not only the surface perturbations but also the variations caused by non-uniformity of the dopant layers.
- **X-ray Edge Absorption Spectroscopy:** GA has developed, using the contact radiography setup with an x-ray spectrometer, x-ray absorption spectroscopy of ICF capsules. Measuring the absorption edge can be used to determine the concentration of elements (Z>17) in the presence of other elements, eliminating the "matrix effect" in XRF. It can also be used to determine the thickness of opaque samples, including a 2D map of the thickness variations [16].
- **Dual-confocal measurement system:** GA has adapted a design from LANL and made it production friendly to provide thickness measurements over a sample area for opaque samples to complement its x-ray edge absorption spectroscopy unit. 3D mapping of ripples and steps in target components to ~1-micron accuracy has been achieved.

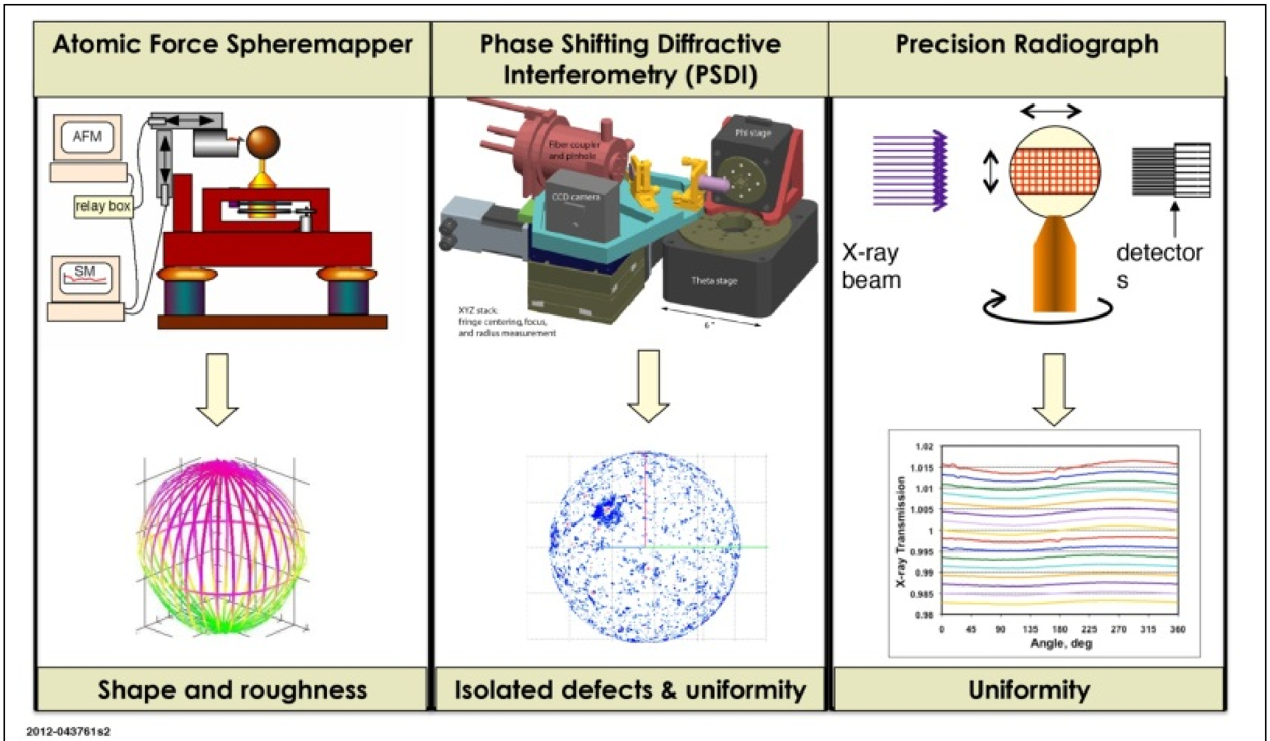

Figure 10. Various metrology tools are used to determine that capsule specifications are met. From left, Atomic Force Spheremapping facilitates full-surface mapping of capsule shape and roughness, Phase Shifting Diffractive Interferometry is used to look for isolated defects and uniformity, and Precision Radiography is used to confirm capsule uniformity.

The current target production workforce at GA consists of nearly 90 personnel; of these, approximately 40 are involved in NIC target fabrication. The GA workforce consists of approximately equal numbers of skilled technicians and scientists/engineers. These include precision machinists and engineers involved in development and production of much of the metal components; chemists, chemical engineers, and materials scientists responsible for development of various coatings and processes for capsule fabrication using different ablator materials, including mandrel fabrication; physicists; and optical engineers who ensure development and implementation of proper metrology required for determining the pedigree of the target components. Though most specialize in a single production type, nearly all are cross- trained in several processes. These GA engineers work through various designs with their counterparts at LLNL and then develop and implement the resulting new designs.

2. Capabilities at LLNL

In addition to the 3000 square foot Class 100 target assembly area, there are two other major LLNL facilities supporting target production. These are the Ignition Target Proofing Station (ITPS), used to cryogenically test layering targets prior to sending them to NIF, and the Contaminated Target Repair Facility, used to repair or modify targets which have been tritium contaminated from ITPS or NIF.

LLNL has a suite of materials characterization techniques that have been applied to target metrology and characterization. Characterization techniques/equipment includes:

Atomic Force Microscopy: A molecular imaging atomic force microscope system is used to measure target material surfaces with nanometer spatial and height resolution.

Ion Beam Characterization (Rutherford backscattering, Elastic Recoil Detection Analysis): A 4-MV ion accelerator is used for target research and development, primarily ion implantation doping and ion beam analysis. Ion implantation has been used for doping ICF ablator capsules with ^{124}Xe atoms and potentially other elements of interest to neutron capture experiments. Ion beam analysis experiments use Rutherford backscattering spectrometry and elastic recoil detection analysis for characterization of the elemental composition of many target components, including the ablator, hohlraum, tent, fill tube, and nanoporous foam scaffold. The accelerator has also been used for the development of post-synthesis processing of nanofoams for ICF applications. Less common ion beam analysis experiments have involved nuclear reaction analysis, particle-induced x-ray emission, and ion-induced desorption spectrometry.

Confocal Microscope 4π Capsule Inspection System: The cleanliness requirement has led to the development of other special fixtures and microscopy tools, such as confocal microscopy for 4π inspection of capsules for particles added during assembly. This system allows particles as small as a few microns to be identified and their location translated to NIF target chamber coordinates for that specific target (see Figure 11).

Focused Ion Beam with Scanning Electron Microscopy (FIB SEM): The focused ion beam characterization allows for site-specific analysis of various capsules by conveniently cutting open the thick coating layers and revealing the internal microstructures, defects (if any exist), and composition details. The FIB measurements offer critical feedback for controlling capsule deposition parameters, and help to fabricate compositionally and microstructurally uniform capsules. FIB techniques are ideal for micrometer-scale area analysis and offers good sampling for millimeter-sized capsules.

Transmission electron microscopy with electron energy loss: Transmission electron microscope (TEM) with electron energy loss spectroscopy offers atomic structure level analysis and extremely high-energy resolution for composition analysis of capsule materials. The information offered by TEM allows for measuring the capsule microstructure down to nanometer spatial resolution and is also critical to controlling the doping atom locations within the capsules. The technique further provides scientific insights for improving capsule fabrication.

Micro x-ray computed tomography: Peering inside optically opaque materials requires penetrating x-rays, acoustic waves, or particles. LLNL's x-ray computed tomography system images materials with a resolution of less than 1 micrometer over a 1-millimeter field of view. This technique provides spatially-resolved opacity that can be translated to density in known compositions and thicknesses.

Double-sided white light interferometer: LLNL developed a double-sided, white light interferometer to scan both sides of a sample simultaneously to provide thickness measurements over the sample area. Combining a "dual roof" mirror and a right angle mirror and a long working distance interferometer objective lens affords equal path length to the front or rear surface of the sample. 3D mapping of ripple and steps in target components to ~1 micron accuracy has been achieved.

At LLNL, the target group has access to beamlines at synchrotron facilities such as the Advanced Light Source at Lawrence Berkeley National Laboratory, Stanford Synchrotron Radiation Lightsource at SLAC National Accelerator Laboratory, and the Advanced Photon Source at Argonne National Laboratory.

These tunable, intense x-ray sources are used to perform scattering, diffraction, absorption (near edge and fine structure), and tomography measurements of target materials and capsules.

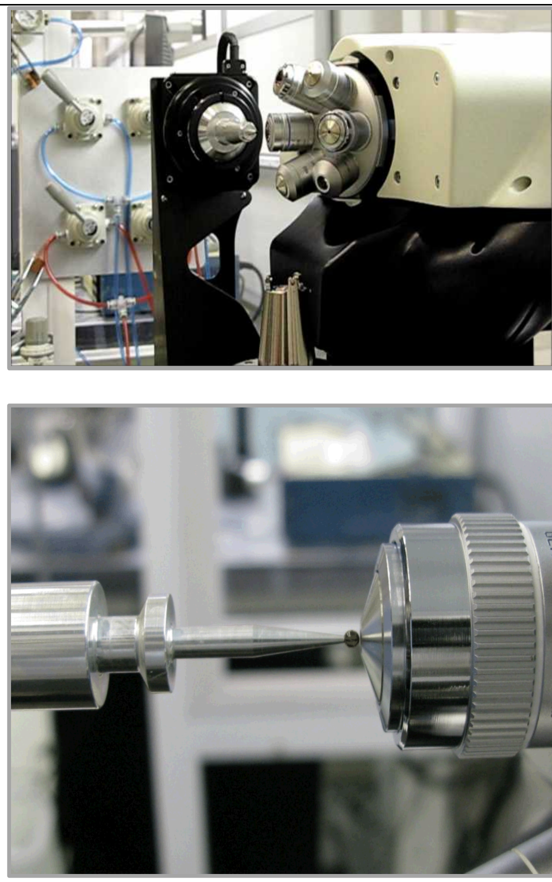

Figure 11. Close-up view of a capsule undergoing a near-4π inspection using a confocal microscope.

During the NIC, the target production workforce at LLNL consisted of 21 technicians and 5 production engineers. Technicians are trained for a primary assembly role and may be cross-trained in up to five additional assembly tasks. There are a minimum of two fully qualified technicians for each assembly task and at least one qualified mentor. The work shift is currently eight hours per day, five days per week. The engineering staff (~8 engineers and four technicians) supports target production by providing design, component, tooling, and assembly expertise to ensure an agile production capability that can respond to changing requirements that evolve from the experimental ignition program. In addition, there are approximately 15 material scientists, chemical engineers, and synthetic chemists plus a contingent of postdoctoral students working in more fundamental areas related to target production, such as material development of foams (nanoporous materials) of varying and graded density, metallic nanoporous foams, ablator materials (such as high density carbon (HDC)), doping of fully dense ablators, and doping of nanoporous materials via atomic layer deposition.

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References

1. K.A. Moreno et al. "Evolution of the Capsule Fill Tube Assembly Production Methods for the National Ignition Campaign," *Fusion Sci. Technol.* **59,** 46 (2011).
2. Z.Z. Johal et al., "Robust Capsule and Fill Tube Assemblies for the National Ignition Campaign," *Fusion Sci. Technol.* **59**, 331 (2011).
3. B. Lairson et al. "Laser Entrance Hole Window Burst and Pressure Deflections at Cryogenic Temperature," *Fusion Sci. Technol.* **59**, 262 (2011).
4. E.T. Alger et al., "NIF Target Assembly Metrology Methodology and Results," *Fusion Sci. Technol.* **59**, 269 (2011).
5. M. M. Biener et al., "Controlled Incorporation of Mid-to-High Z Transition Metals in CVD Diamond," *Diamond & Related Materials* **19**, 643 (2010).
6. S.J. Shin et al., "Xenon doping of glow discharge polymer by ion implantation," *Applied Physics Letters* **111,** 096101 (2012).
7. M. Wiora et al., "Grain size dependent mechanical properties of nanocrystalline diamond films grown by hot-filament CVD," *Diamond & Related Materials* **18**, 927 (2009); M. Wolfer et al., "Crystallographic anisotropy of growth and etch rates of CVD diamond," *Diamond & Related Materials* **18**, 713 (2009).

8. M. Stadermann, S.A. Letts, and S. Bhandarkar, “Improvements to Formvar Tent Fabrication Using the Meniscus Coater,” *Fusion Sci. Technol.* **59**, 58 (2011).

9. S. Bhandarkar, T. Parham, and J. Fair, “Modeling and Experiments of Compressible Gas Flow Through Microcapillary Fill Tubes on NIF Targets,” *Fusion Sci. Technol.* **59,** 51 (2011).

10. S.A. Letts et al., “Quality Assurance and Characterization of Adhesives used for NIC Target Assembly,” *Fusion Sci. Technol.* **59**, 63 (2011).

11. R.C. Montesanti et al., “Lessons from Building Laser-Driven Fusion Ignition Targets with the Precision Robotic Assembly Machine,” *Fusion Sci. Technol.* **59,** 70 (2011).

12. A.J. Detor et al., “Stress and microstructure evolution in thick sputtered films,” *Acta Materialia* **57,** 2055 (2009); J. Biener et al., “Diamond Spheres for Inertial Confinement Fusion,” *Nuclear Fusion* **49**, 112001 (2009); L.A. Zepeda-Ruiz et al., “Understanding the Relation between Stress and Surface Morphology in Sputtered Films: Atomistic Simulations and Experiments,” *Appl. Phys. Lett.* **95**, 151910 (2009); L.A. Zepeda-Ruiz et al., “Surface Morphology Evolution During Sputter Deposition of Thin Films—Lattice Monte Carlo Simulations*,” Journal of Crystal Growth* **312**, 1183 (2010); K.L. Sequoia et al., “Increased X-Ray Opacity of GDP Capsules from High Intensity X-Ray Exposure,” *Fusion Sci. Technol.* **59**, 35 (2011).

13. K. Youngblood et al., “Improving the Reproducibility of the Radial Argon Concentration in Beryllium Shells,” *Fusion Sci. Technol.* **59**, 126 (2011).

14. H. Huang et al., “Metrology Statistics For NIF Tuning Campaign,” *Fusion Sci. Technol.* **59,** 26 (2011).

15. A.Q.L. Nguyen et al., “Characterization of Isolated Defects for NIF Targets using PSDI with an Analysis of Shell Flipping Capability,” *Fusion Sci. Technol.* **55,** 399 (2009).

16. J.R. Fong et al., “X-Ray Absorption Spectroscopy for ICF Target Characterization,” *Fusion Sci. Technol.* **55,** 367 (2009).